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Adaptive control of a synchronous motor via a sliding mode decomposition technique

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Abstract This paper presents a decoupled control strategy using time-varying sliding surface-based sliding-mode controller for speed control of permanent magnet synchronous motor (PMSM). The decoupled method provides a simple way to achieve asymptotic stability for a PMSM by dividing the system into two subsystems electrical and mechanical systems. The simulation results for PMSM are presented to demonstrate the effectiveness and robustness of the method. Comparing this controller with pulse width modulation (PWM) controller for the same motor.

1. Introduction

In recent years, sliding-mode control (SMC) has been suggested as an approach for the control of systems with nonlinearities, uncertain dynamics and bounded input disturbances. The most distinguished features of the SMC technique are: (i) insensitivity to parameter variations, (ii) external disturbance rejection and (iii) fast dynamic responses. However, there is undesirable chattering in the control effort and bounds on the uncertainties required in the design of the SMC. The uncertainties usually include unmodel dynamics, parameter variations and external disturbances [1–4]. If the actual bounds of the uncertainties exceed the assumed values designed in the controller, stability of the system is not guaranteed.

Like other conventional control structures [5–7], the design of sliding-mode controllers needs the knowledge of the mathematical model of the plant, which decreases the performance in some applications where the mathematical modeling of the system is very hard and where the system has a large range of parameter variation together with unexpected and sudden external disturbances [8–11].

In this paper, a decoupled sliding-mode control (DSMC) design strategy is used to control the speed of PMSM. The motor system is divided into two subsystems with different switching surfaces to achieve the desired speed.

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2. PMSM mathematical model

PMSM drives are becoming more popular and replace classical motors in industrial applications, machine tools and residential applications. In a PMSM the excitation is provided by means of using permanent magnets mounted on the rotor. PMSMs present numerous advantages like high efficiency, high torque to inertia ratio, high power density, reliability and long life.

For control unit design the synchronous motor is modeled in rotating rotor coordinates $\{d, q\}$. Unlike in stator coordinates $\{a, b, c\}$, where the signals have to be modulated on sine waves in order to propel the machine, the waveform of all variables in rotor coordinates is unconstrained and the modulation is carried out implicitly during transformation from rotor to stator coordinate.

Eq. (1) shows the transformation matrix between 3 phase currents (I_{abc}) and dq-courrents (I_{dq}):

$$I_{dq} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}. \quad (1)$$

The PMSM model is given by the following differential equations as [12]:

$$\begin{aligned} L\dot{i}_d &= -Ri_d + p\omega L_q i_q + u_d \\ L\dot{i}_q &= -Ri_q - p\omega L_d i_d - \lambda p\omega + u_q \\ T_e &= 1.5p[\lambda i_q + (L_d - L_q)i_d i_q] \\ J\dot{\omega} &= T_e - \mu\omega - T_L \\ \dot{\theta} &= \omega, \end{aligned} \quad (2)$$

where u_d, u_q: the rotor voltages in $\{d, q\}$ coordinates (V); i_d, i_q: rotor currents in $\{d, q\}$ coordinates (A); θ: the electrical rotor position (rad); ω: the angular velocity of the motor shaft in electrical (rad/s); R_d, R_q: the winding resistance of d and q axis (Ω); L_d, L_q: the inductance of d and q axis (H), λ: rotor magnet flux linkage (Wb); J: the rotor and shaft inertia (kg m^2); μ: the coefficient of friction (N.m.s); p: the number of permanent magnet pole pairs; T_L: the disturbing external torque (N.m) and T_e: the motor torque (N.m).

For $L_d = L_q = L$ then the motor torque will be

$$T_e = 1.5p\lambda i_q = Ki_q, \quad (3)$$

where k is the motor torque constant.

Substitution in Eq. (2), so the model can be written as:

$$\begin{aligned} L\dot{i}_d &= -Ri_d + p\omega L i_q + u_d \\ L\dot{i}_q &= -Ri_q - p\omega L i_d - \tfrac{2}{3}k\omega + u_q \\ J\dot{\omega} &= T_e - \mu\omega - T_L \\ \dot{\theta} &= \omega. \end{aligned} \quad (4)$$

3. Motor model in state space equations

Let

$$\begin{aligned} x_1 &= i_d \\ x_2 &= i_q \\ x_3 &= \omega, \end{aligned} \quad (5)$$

then the model can be written as

$$\begin{aligned} \dot{x}_1 &= -\tfrac{R}{L_d}x_1 + px_3x_2 + \tfrac{1}{L_d}u_d \\ \dot{x}_2 &= -\tfrac{R}{L_q}x_2 - px_3x_1 - \tfrac{2}{3L_q}kx_3 + \tfrac{1}{L_q}u_q \\ \dot{x}_3 &= -\tfrac{\mu}{J}x_3 + \tfrac{1}{J}kx_2 - \tfrac{1}{J}T_l, \end{aligned} \quad (6)$$

so the model can be written as :

$$\begin{bmatrix} \dot{i}_d \\ \dot{i}_q \\ \dot{\omega} \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} \frac{-R}{L} & px_3 & 0 \\ -px_3 & \frac{-R}{L} & -\frac{2K}{3L} \\ 0 & \frac{K}{J} & -\frac{\mu}{J} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ \frac{1}{J} \end{bmatrix} T_l. \quad (7)$$

From Eqs. (6) and (7), it is obvious that the dynamic model of PMSM is highly nonlinear because of the coupling between the speed and the electrical currents, in addition to the saturation effect of the magnetic circuit and the existing viscous friction.

The PMSM parameters are: 1.1 KW, 3000 RPM, $R = 2.875\,\Omega$, $L_d = L_q = 8.5$ mH, $P = 4$ pair of poles (8 poles), $J = 0.8 \times 10^{-3}$ kg m^2, $\mu = 1$ N.m.s.

4. Sliding mode control and decoupling

There is currently a large interest in sliding mode control algorithms due to their robustness properties and possibilities to decouple a high dimensional design problem into a set of lower dimensional independent sub-problems.

The switching surface: Consider a general type of system represented by the state equation,

$$\dot{x} = f(x, u, t). \quad (8)$$

The control $u(x, t)$ with its respective entry $u_i(x, t)$ has the form

$$u_i(x, t) = \begin{cases} u_i^+(x, t) & if \quad s_i(x) > 0 \\ u_i^-(x, t) & if \quad s_i(x) < 0 \end{cases}, \quad (9)$$

where $u_i^+(x, t)$, $u_i^-(x, t)$ and $s_i(x)$ are continuous functions. $s_i(x)$ is an $(n-1)$ dimensional *switching function*. Since $u_i(x, t)$ undergoes discontinuity on the surface $s_i(x) = 0, s_i(x) = 0$ is called a switching surface or switching hyperplane as in Fig. 1.

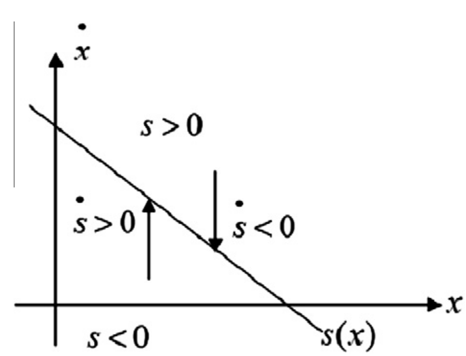

Figure 1 The sliding surface (S).